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EVALUATING 1 & 2D DIMENSIONAL MODELS FOR FLOODPLAIN INUNDATION MAPPING

by

M.G.ANDERSON

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Professor M G Anderson

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Professor M G Anderson

School of Geographical Sciences, University of Bristol, University Road, Bristol, BS8 1SS, UK. Tel: +44 117 9287871 Fax: +44 117 928 7878

SUMMARY

This document reports on the work undertaken in the first 9 months of the project.

BACKGROUND

The aim of this project is to undertake a feasibility study into the potential utility of integrating high resolution two dimensional finite element flow models and Geographical Information Systems technology.

The initial phase of this research concerns the construction of an operational high resolution flow model for a 60km reach of the Missouri River between Gavins Point Dam and Maskell gauging station. Specifically, the contract seeks to produce a CRREL report and to assess data needs for 2D FE models for river flow inundation.

This report contains a brief review of progress on this work unit during months 6-9 of the research contact.

PROGRESS

This reporting period saw the **production of the draft CRREL report on the contract** – working title "*Towards an evaluation of 1 & 2D models for floodplain inundation mapping*".

A copy of the draft report is attached.

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TOWARDS AN EVALUATION OF 1 AND 2-D MODELS FOR FLOODPLAIN INUNDATION MAPPING

Christopher N. Smith, Paul D. Bates and Malcolm G, Anderson

DRAFT
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1. INTRODUCTION

In this report we address the numerical simulation of reach scale free surface. For such flows construction of accurate prediction models remains a fundamental research problem in hydrology and hydraulics. Such studies are not only of importance to engineers and planners engaged in the water resources field but are also an important pre-requisite for modelling investigations of sediment transport (James, 1985; Pizzuto, 1987; Marriot, 1992; Falconer and Chen, 1996; Walling *et al.*, 1996), contaminant transport (Marron, 1989; Burt *et al.*, 1993), floodplain ecology (Jolly, 1996; Richards *et al.*, 1996) and catchment hydrology (Beven, 1985; Abbott *et al.*, 1986; Beven *et al.*, 1987) which either require hydraulic data as an input or incorporate a submodel for hydraulic processes. For all these tasks we require a model capable of accurately predicting spatially distributed hydraulic variables such as water depth and flow velocity. A fundamental constraint to the development of such a model is the lack of suitable calibration and validation data sets. Whilst it is now possible to develop high space/time resolution prediction schemes, current data capture techniques do not allow the utility of such developments to be fully assessed. The purpose of this report is to review recent progress in hydraulic modelling and examine the extent to which recent advances in the remote sensing of flood hydrology have the potential to overcome current data constraints thereby leading to an integration of remote sensing and modelling methodologies.

2. REVIEW OF RECENT PROGRESS IN HYDRAULIC MODELLING

2.1 Background

Progress in hydraulic modelling over the last decade has led to considerable improvements in our ability to simulate river flow problems. The impetus for this progress has come from a number of fields and incorporates improvements in process understanding, mathematical and numerical developments and improvements in available computational power. Large scale flume studies (see for example Knight and Shiono, 1993; Sellin and Willetts, 1996) have demonstrated the complexity of river flow processes which effectively invalidate one dimensional models for certain classes of flow problem (Knight and Shiono, 1996). A need has therefore arisen to develop higher resolution hydraulic models (two and three dimensional) to account for the impact of these processes during river flood events. Concurrently, developments in Computational Fluid Dynamics (CFD) have led to the development of a number of techniques which have enabled this need to be met. Stable numerical techniques for free surface flow problems have been developed. For example, the Streamline Upwind Petrov Galerkin developed by Brookes and Hughes (1982) eliminates spurious oscillations from numerical solutions of the Navier-Stokes equations without adding artificial diffiusivity. Element-by-element matrix storage techniques (Carey and Jiang, 1986; Hervouet, 1992; Binley and Beven, 1993) have reduced computer storage requirements and improved efficiency, allowing spatially complex higher dimensional problems to be simulated. Lastly, and of critical importance to flood inundation problems, algorithms have been developed to simulate dynamically moving inundation extent boundaries (Lynch and Gray, 1980; King and Roig, 1988). Thus, the last decade has seen a significant stimulus to develop two dimensional, or higher, numerical models for flood inundation problems, while at the same time a series of technical advances has rendered this goal attainable.

Two and three dimensional modelling approaches have now been developed for application to a number of free surface flow problems. Such models solve some form of the Navier Stokes equations, such as the St. Venant, or shallow water, equations in conjunction with a number of approximations to represent such processes as turbulence and boundary friction (see for example Hervouet and Van Haren, 1996; Lane, 1997). An appropriate discretization of the domain geometry and topography is developed to define a network of computational nodes where the above equations can be solved by some numerical procedure. Codes have been developed using a variety of numerical methods including finite difference (Zeilke and Urban, 1981), finite element (Gee *et al.*, 1990; Bates *et al.*, 1992) and finite volume (Lane *et al.*, 1994). This solution in space is then projected forward in time using a further numerical procedure, typically a finite difference scheme, to give a dynamic simulation. Given appropriate boundary conditions, estimates of water depth and flow velocity may thus be obtained at each computational node at each time step. In particular, a series of studies have focused on the development of hydraulic models for long reach flood inundation problems. Until recently, application of hydraulic models to free surface flow problems has been characterised by three specific attributes: the scale of application was small (0.5-2 km) and focused on the analysis of detailed flow patterns; the main channel was rarely resolved separately from the floodplain and the entire domain was inundated during the simulation. However, most floodplain inundation problems of practical interest occur at long reach scales (10-60 km) and involve a dynamic flood inundation boundary. As a consequence there is a need to represent dry areas within the computational domain. A number of models have therefore been developed which are capable of application at this scale and which incorporate algorithms to account for wetting and drying processes (see for example Gee *et al.*, 1990; Baird *et al.*, 1992; Feldhaus *et al.*, 1992; LeClerc *et al.*, 1992; Bates *et al.*, 1995). Given the

scale of the problem, the above approaches all adopt a two dimensional finite element approximation to the flow field which enables complex topography to be represented with a minimum number of computational points.

Such simulations are, however, by no means straightforward and in developing an appropriate flood simulation model a number of issues have to be considered. Firstly, the model must represent a complex set of hydraulic processes operating over a range of time and length scales. These range from turbulence at micro-scales, for example 1-10 cm and 1-10 seconds, to the scale of the flood wave itself, which may be hundreds of kilometres in length and persist for several days (see Bates and Anderson, 1993 for a more complete discussion). The level of detail at which processes can be represented is dependent on the scale of the simulation. A compromise therefore exists between processes representation and scale, with the modeller being required to make a number of subjective decisions regarding which processes are relevant for particular applications. Secondly, field observations have shown that floodplains, islands and channel bars possess a complex micro topography that may have a significant effect on both local hydraulic and sediment transport processes (Walling *et al.*, 1986; Walling *et al.*, 1991) as well the inundation extent (Bates and Anderson, 1996) for a particular recurrence interval flood. Given this complexity of process and initial condition specification, hydraulic models must simplify actual physical processes. This, in conjunction with the impossibility of obtaining complete *a priori* knowledge of parameters such as boundary friction in distributed models, means that recourse must inevitably be made to calibration procedures in any practical application to achieve a correspondence between model predictions and field data.

2.2 Issues of Calibration and Validation

Although calibration is a necessity, it may lead to a number of potentially significant constraints on our ability to further develop this class of model. In effect the numerical procedure attempts to solve a system of simultaneous equations where there are many more unknowns than equations. The objective behind estimating these unknowns is an attempt to obtain a match with some test data set. However, given that data availability is limited, particularly when compared to the number of data points that are unknown, the degrees of freedom present within the modelling procedure are such that the solution obtained may not be unique. Thus, more than one set of calibration parameters may fit the available data. This is particularly true of inundation extent predictions. Available calibration and validation data for river reaches predominately consist of observations of bulk flow properties such as discharge. These are typically available only at the reach outflow, as in the River Stour example above. It may be entirely possible to develop a number of calibrations for this problem which match the available downstream discharge record but give different predictions of flood inundation extent. For example, Bates *et al.* (1996) studied a hypothetical channel/floodplain domain using a Monte Carlo procedure to generate boundary friction and turbulent viscosity parameters for input into a two dimensional finite element model. They showed that a range of calibrations could be obtained that gave equal acceptability in terms of their ability to predict the downstream outflow hydrograph but which gave inundation extents varying between 80 and 93% of the total floodplain area. Thus, incorrect internal process representation can produce a 'correct' result at the reach outflow due to an inability to constrain the calibration procedure to a unique solution (see for example Beven, 1989; Konikow and Bredehoeft, 1992; Fawcett *et al.*, 1995). Moreover, the results of this study show that we are unlikely to be able to calibrate complex hydraulic models using hydrograph data alone. Recent modelling developments have enabled the

potential for prediction to far outstrip our ability to collect sufficient calibration and validation data. For example, the River Stour simulation discussed above generated approximately 1.17 x 10^9 items of data. This compares to an available data set of 248 discharge measurements. Moreover, these data are not spatially distributed and we are thus unable to utilize the full potential of the model.

A lack of spatially distributed calibration and validation data therefore currently constrains our ability to further develop high resolution flood hydraulic models. In order to determine a research design for future model development we require sufficient data internal to the model computational domain to both achieve a calibration which constrains the number of possible solutions as far as possible and to validate this prediction model using a split-sample approach. Due to the problems with the collection of hydraulic data, such as flow velocity, during flood events an obvious focus for attention should be direct observation of flood inundation extent. Not only is this variable sensitive to small changes in water surface elevation due to shallow floodplain, island or mud flat bed gradients, it has also been shown to require an additional set of approximations over and above those needed to solve the controlling equations. Its accurate prediction is therefore a good test of model capabilities and of significant practical interest. In this context remote sensing methods, both airborne and satellite, have significant potential for acquiring such information at a spatial scale commensurate with model resolution.

2.3 Key Features of the Study

- ***The use of a high resolution model, in both space and time, along with wetting and drying algorithms for representing moving flow field boundaries allows dynamic inundation predictions.***
- ***For the first time model predictions are validated on this scale in both time and space using multiple data sources. The data sources are internal stage data at two sites, supplied by the USACE Missouri River District (MRD), and satellite imagery, supplied by the Remote Sensing and Geographic Information Systems Center at USACE Cold Regions Research and Engineering Laboratory (CRREL).***
- ***The influence of bathymetric data on the model predictions is studied for its potential in aiding future data collection strategy.***

3. A TWO DIMENSIONAL MODEL FOR FLOODPLAIN INUNDATION PREDICTION

3.1 2D Model Selection for the Study

The TELEMAC system is a series of computer programs utilising finite element techniques for simulating hydraulic situations. The system includes pre- and post-processing components and offers solutions in two- and three-dimensions. It also contains facilities for sediment and contaminant transport (SUBIEF) and sand transport (TSEF). The full system is further outlined in Figure 3-1. All the components of the system have common file formats and are written in the high level language FORTRAN 77. This enables easy file transfer between components of the system and allows model users to modify parts of the code as desired for specific applications.

The TELEMAC system contains both two- and three-dimensional versions. The three-dimensional version (TELEMAC-3D) has advantages in many applications where vertical velocity variations are important such as small scale and oceanic studies but in large scale fluvial applications depth averaged calculations are adequate. Indeed the equations used in nearly all fluvial hydraulic models derive from the depth averaged equations known as the Shallow Water or St. Venant Equations, TELEMAC-2D being no exception. The third dimension, though initially appealing, would simply add to the computational and data demands. Descriptions of TELEMAC-3D can be found in Hervouet *et al.* (1994), Hervouet and Janin (1994) and Hervouet and Van Haren (1996). TELEMAC-2D is however used throughout the work presented here and is now discussed in more detail.

Figure 3-1: The TELEMAC-2D modelling system (after Hervouet and Lang, 1995).

The main features of TELEMAC-2D are listed by Hervouet *et al.* (1994) as:

- structured or non structured meshing,
- use of Cartesian or spherical co-ordinates,
- subcritical and supercritical regimes (with hydraulic jumps),
- various momentum source terms : bottom friction, wind stress atmospheric pressure, Coriolis force,
- turbulence modelling (k-epsilon model),
- equation on temperature or a substance concentration,
- treatment of tidal flats,
- many types of boundary conditions including free slip condition and incident waves.

Many of these are of minimal importance for fluvial applications but are necessary for the diverse nature of cases that TELEMAC-2D can be applied to. A wide range of test cases are illustrated in the TELEMAC-2D (version 3.0) validation document (Cooper, 1996) prepared to substantiate the explicit claims made about the applicability and accuracy of the computer code. The test cases illustrated range from the Western European Coast and the Mersey estuary UK, to flows around bridge piers and over a weir. On a scale more relevant to this study dam breaks, flow at a river confluence and the simulation of a flood event on the River Culm, UK are also shown. A new version of TELEMAC-2D is released annually. All of the simulation in this report have been carried out using version 3.0, released in 1995.

3.2 Shallow water equations

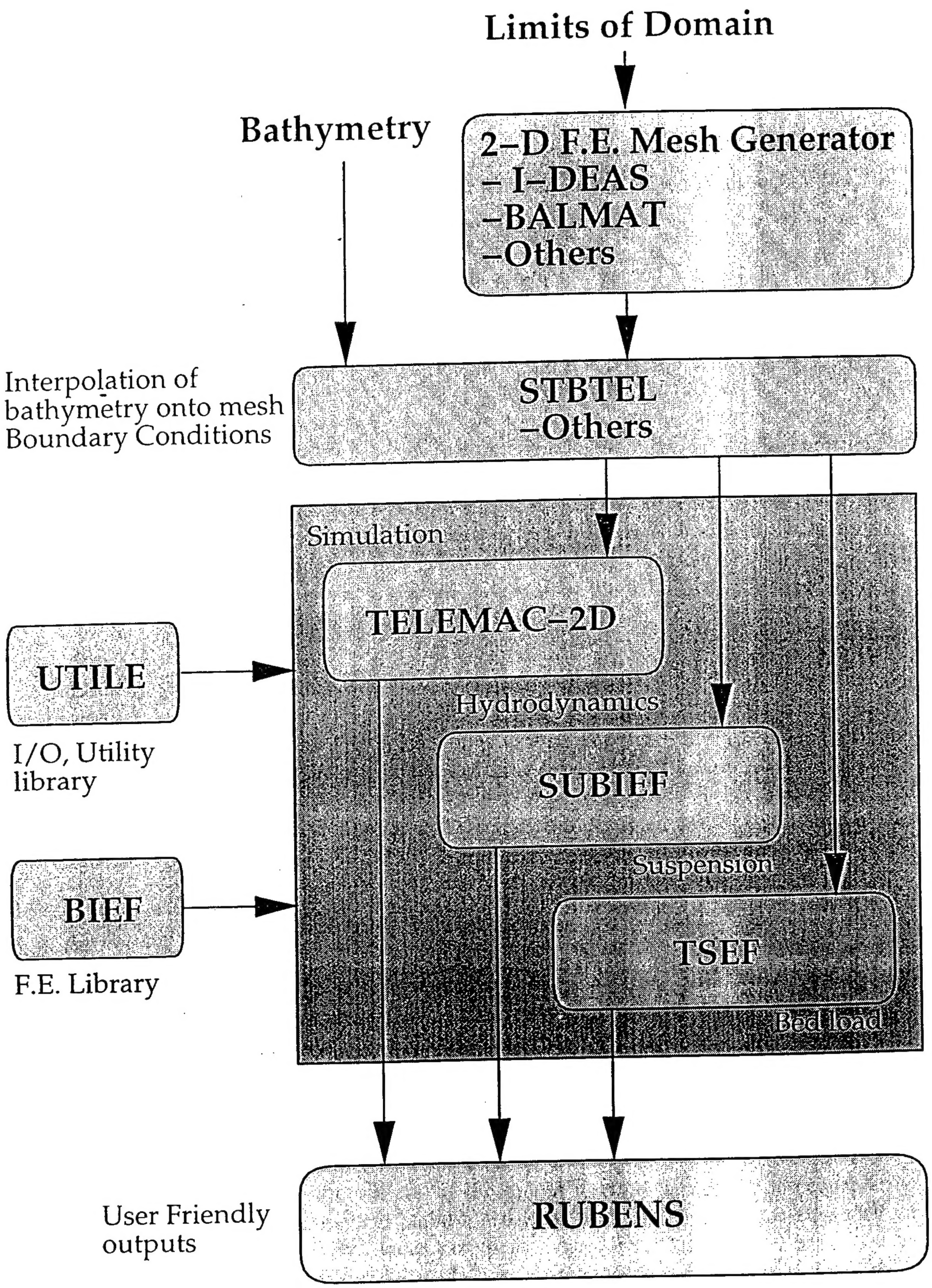


Figure 3-1 The TELEMAC-2D modelling system (after Hervouet and Lang, 1995).

TELEMAC-2D solves the shallow water equations (SWE), the depth averaged version of the fully three dimensional Navier Stokes equations of fluid flow. All of these conditions are commonly met in rivers, estuaries and seas making the choice of these equations over the full three dimensional Navier Stokes equations valid for the applications of the model (Cooper, 1996).

The choice of formulation of the SWE used in TELEMAC-2D is not obvious. A conservative form would seem better but divisions by the water depth are needed to produce the velocity field, hence causing problems in dry areas of the model domain. Hence a non-conservative form is preferred. Moreover numerical stability analysis also favours the non-conservative version of the equations. Using finite element methods mass conservation can be ensured with non-conservative equations. Two versions of these non-conservative equations have been developed, the celerity-velocity version and the depth-velocity version. The depth-velocity version are marginally favoured as they are easier to apply mass-conservation techniques to (Hervouet and Janin, 1994). These equations are shown below:

$$\frac{\partial h}{\partial t} + \mathbf{u}.\mathbf{grad}(h) + h.\mathrm{div}(\mathbf{u}) = 0 \qquad \text{Equation 3-1}$$

$$\frac{\partial u}{\partial t} + \mathbf{u}.\mathbf{grad}(u) + g\frac{\partial h}{\partial x} - \mathrm{div}(v.\mathbf{grad}(u)) = S_x - g\frac{\partial Zf}{\partial x} \qquad \text{Equation 3-2}$$

$$\frac{\partial v}{\partial t} + \mathbf{u}.\mathbf{grad}(u) + g\frac{\partial h}{\partial y} - \mathrm{div}(v.\mathbf{grad}(v)) = S_y - g\frac{\partial Zf}{\partial y} \qquad \text{Equation 3-3}$$

where:

h : water depth
u, v : velocity components
g : gravity
Zf : bottom elevation.
Sx, Sy :Source/sink terms (bottom friction, wind, etc.)
v : eddy viscosity

h, u & v are the unknown variables.

Equation 3.1 being the continuity equation, 3.2 and 3.3 the force-momentum equations. Full derivations can be found in Norton *et al.* (1973).

The TELEMAC system uses finite element methodology to solve the shallow water equations to produce values of water depth (h) and two velocity components (u and v) at all points in the model domain. To achieve this the domain must be discretized into a grid or mesh, usually made up of linear triangles (unstructured grid) for flexibility. The mesh is created outside TELEMAC using specialised mesh generation software such as SDRC I-DEAS or BALMAT. The mesh is then integrated with the topographic data to produce a geometry file that is then used in the TELEMAC-2D simulation. The mesh consists of a series of node points, the vertices of the triangles with a elevation (z) value, where the equations are solved

and the triangles themselves are the elements. The geometry notation used is shown in Figure 3-2.

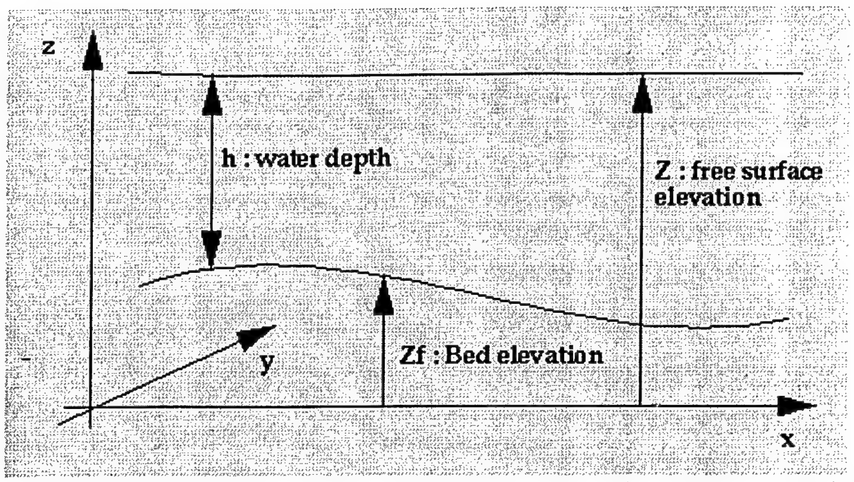


Figure 3-2 The geometry notation used in TELEMAC-2D (after Hervouet and Van Haren, 1995).

3.3 Boundary conditions

There are two main types of boundary condition that can be used, solid boundaries and liquid boundaries. The boundaries described here are round the sides of the model domain and through the bed of the model. All boundary conditions are assigned on a node by node basis. Solid boundaries are no flux (impermeable) and incorporate a friction factor (Hervouet and Van Haren, 1995). Liquid boundaries allow a flux across them. They are more difficult to deal with as they suppose the existence of a fluid area that is not part of the calculation domain but can however influence it. This influence is described through the boundary condition. There are four types of liquid boundary, entry and exit with supercritical flow (Froude number >1) and entry and exit with subcritical flow (Froude number<1). Incident waves and prescribed flowrates can be incorporated through these 4 boundary types. Hervouet and Van Haren (1995) describe these boundary conditions more fully.

3.4 Physical parameter options

Physical representation of parameters is essential in models such as TELEMAC-2D in order to apply them to different applications. TELEMAC-2D includes numerous physical parameters. The most important are discussed in this section.

There are six options in TELEMAC-2D for representing bed friction, these are:

- No friction
- Linear friction
- Chezy's law
- Strickler's law
- Manning's law
- Nikuradse's law

The applied friction coefficient is converted to force terms in the x and y directions at each computational node which is then fed into the Shallow Water Equations (in the source terms Sx and Sy - see section 3.2, Equation 3-2 and Equation 3-3). In reality the bed friction force is a quadratic function of velocity so the no friction and linear law are rarely used in practical applications (Hervouet and Van Haren, 1996). The Chezy, Strickler and Manning laws are all closely related and utilise the quadratic function mentioned and are all described more fully by Hervouet and Van Haren (1995). Nikuradse's law calculates a Chezy coefficient from the water depth (h) and grain size of the bed material which is then converted into a force term. Which of these laws that is used is not very important as they are very closely related and friction coefficients can easily be converted between them. The choice rests with the model user.

Applications of TELEMAC-2D to river and estuaries generally involve wetting and drying areas of the model domain. For example the tidal simulation in the Mersey estuary and the flood event on the River Culm, both described by Cooper (1996), involve this type of behaviour. The ability of the model to deal with this sort of behaviour is therefore of vital importance but is problematic. The behaviour in the dry zones, where divisions by the water depth (h) in the calculations, can cause spurious terms to appear as h tends towards zero.

Two solutions to this problem are available in TELEMAC-2D, both described in more detail by Hervouet and Van Haren (1995),

- solving the equations everywhere and coping with the spurious terms.
- removing the dry zones from the computational domain.

The first is the simplest but corrections must be applied in the dry zone. In dry areas the water surface gradient becomes that of the bottom topography but this cannot be allowed to act as a driving force in the momentum equation.

The second method removes the dry zone from the computational domain and is often called the "moving boundary technique". In TELEMAC-2D this is achieved efficiently, avoiding the need to redefine the mesh at each time step, by keeping the elements in the mesh but cancelling their existence through the use of an array set to 0 for dry elements and 1 for all others.

Partially dry elements are another important area, especially where the elements are large such as in the Missouri River model. These are coped with in TELEMAC-2D by a sophisticated method that allows the water depth to go to zero within an element. This compares favourably with the usual techniques of keeping the elements fully wet or excluding partially dry elements (Figure 3-3).

3.5 Summary of the TELEMAC-2D system

TELEMAC-2D is a high resolution space/time distributed hydraulic model that solves the Shallow Water Equations for fluid flow using finite methodology. The model can be used in a wide variety of scenarios including those involving wetting and drying fronts within the model domain. Bed friction and turbulence are represented in the model through the use of physically based parameters.

TELEMAC-2D can therefore be seen to be well specified for the type of fluvial application that is of interest in this study. The code has been shown to work, through the report of

Cooper (1996), in a wide range of cases. Success in any individual situation is however dependant on the data provided, physical and numerical parameters used. How these important factors have been determined in the Missouri River model case is the subject of the next section.

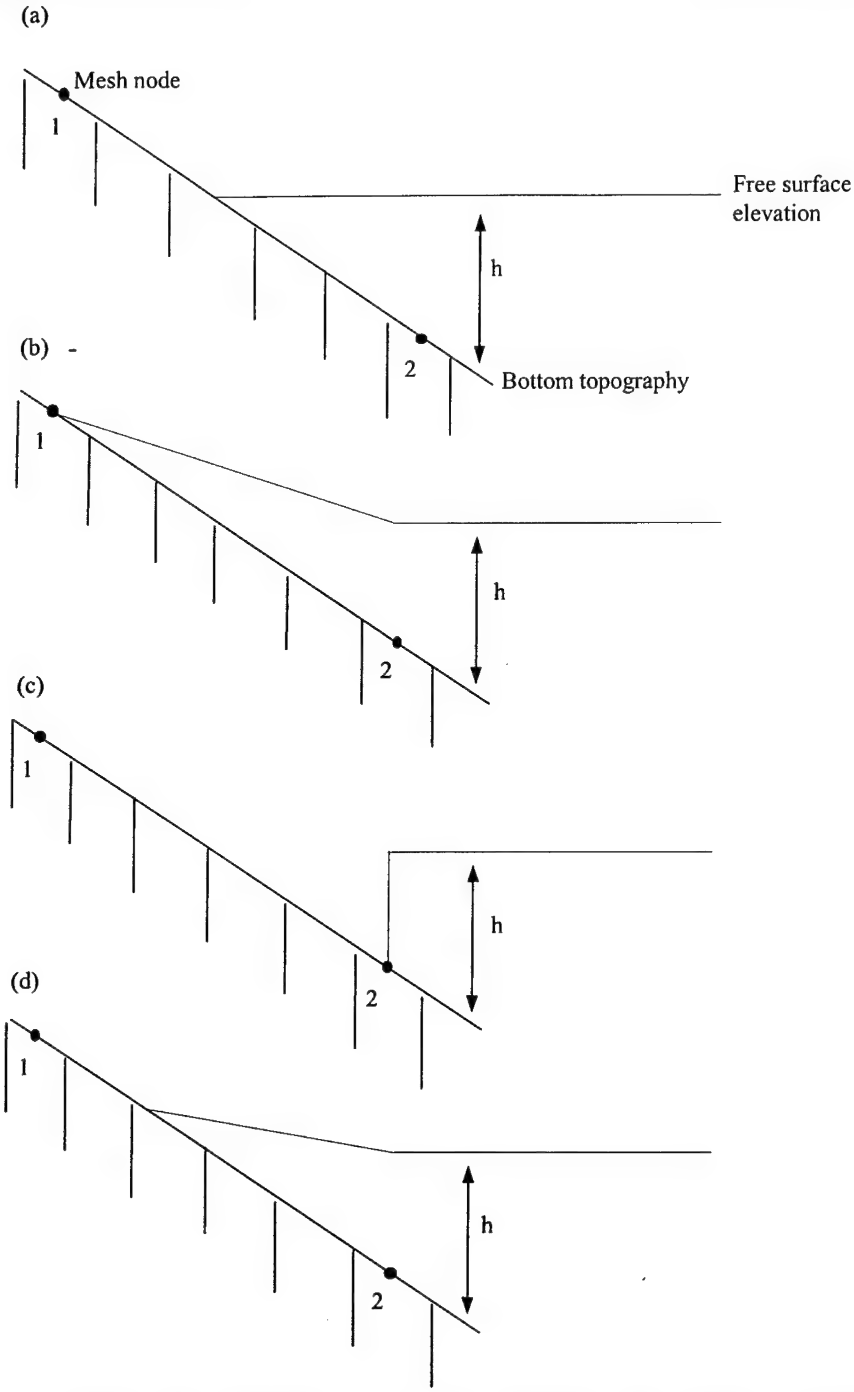


Figure 3-3 Partially dry elements: (a) the real situation, (b) element remaining fully wet introducing spurious momentum terms, (c) element exclusion method and (d) TELEMAC-2D method keeping the element partially dry (after Price, 1997).

4. THE MISSOURI RIVER MODEL

4.1 Missouri River Reach

The reach of the Missouri River being used for this modelling study is that from Gavins Point Dam, South Dakota, to the gauging station at Maskell, Nebraska (Figure 4-1). The reach covers river miles 811 to 776 making it 35 miles or 55 km long. The channel varies in width between 300m and 1200m. The channel slope is very low, dropping only about 12 metres along its 55 km length, giving a gradient of 0.02%. The bed material in this channel is sand which is fairly mobile but the channel banks have been strengthened or stabilised along much of the reach. There are several islands along the reach several of which are permanent. There is one major tributary, the James River, that joins the main stem at river mile 800 adjacent to the James River Island.

The flow out of Gavins Point Dam is regulated to minimise the risk of flooding downstream, hence the reach being modelled is very unlikely to attain out of bank conditions. The flow in the James River is however naturally variable. The model of this system can therefore remain as channel only. River flow data is available at several points along the reach on an hourly basis. Table 4-1 shows the data availability and gauge locations (also Figure 4-1).

Table 4-1 Gauge station location and data availability.

Gauging Station	Distance from top of reach (km)	Data Available
Gavins Point Dam, SD.	0	Flow rate
Yankton, SD.	7.5	Flow rate and Stage
Gayville, SD.	21.5	Stage
Maskell, Neb.	55	Stage
Scotland, SD.	53 km up James River from confluence	Flow rate and Stage

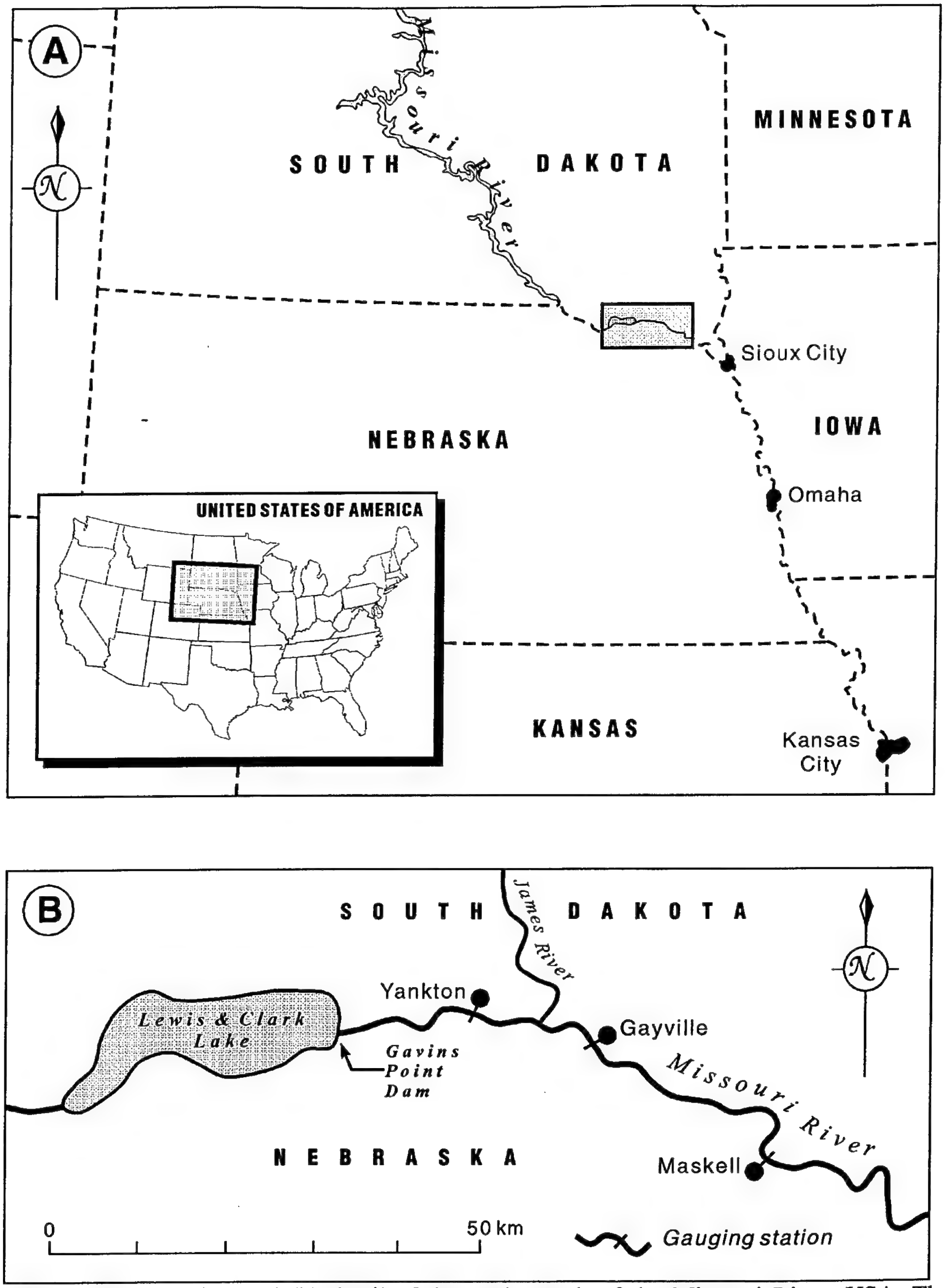


Figure 4-1a) Location and (b) detail of the study reach of the Missouri River, USA. The modelled reach is from Gavins Point Dam to Maskell and includes the gauging stations at Yankton and Gayville.

The flow from the James River gauge at Scotland, South Dakota, is routed using a simple one-dimensional kinematic wave model to the required location on the main model input boundary when necessary.

The observed data for the Missouri model is of very high quality and quantity. The available data sets are of special value because they allow both detailed point comparisons using the stage data at two sites, Yankton and Gayville, and spatially distributed comparisons using the satellite imagery. Using this data the performance of the Missouri River model can be comprehensively analysed.

4.2 Producing the finite element mesh

The finite element mesh for the model must be created by first defining the boundary of the model domain and secondly discretizing this area into elements.

The boundary of the 2D model was defined by digitising round the edge of the river as represented on United States Department of the Interior 7.5 minute quadrangle series maps. The use of wetting and drying algorithms in the model enable the flow field boundary to be calculated within this outer boundary thus allowing this boundary to be fairly loosely defined. The digitised boundary was then converted to Universal Transverse Mercator (UTM) metre co-ordinates for compatibility with the metric scale used by TELEMAC-2D. The boundary of the model (with TELEMAC-2D's metric scale), which includes three permanent islands, is shown in Figure 4-2.

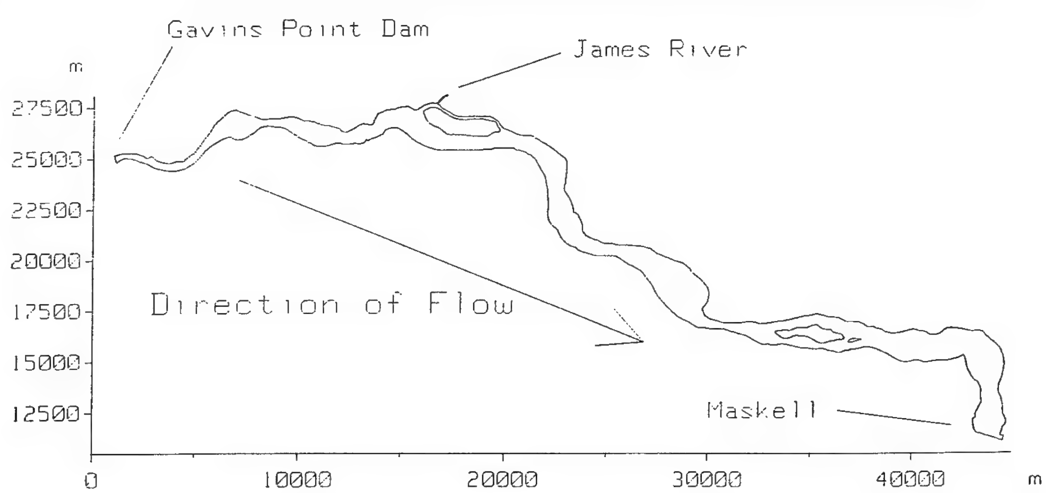


Figure 4-2 The boundary delineation of the Missouri River model.

A mesh of triangular elements must be made within the model domain to facilitate the finite element solution technique. The finite element mesh used with the Missouri model were generated inside the prescribed boundary using the mesh generation package BALMAT and consisted of near equilateral triangles in order to increase the accuracy and minimise mass conservation errors. This consisted of 5969 nodes and 10437 elements with an average size of approximately 100 m^2 and is shown in Figure 4-3.

Figure 4-3 Finite element mesh of the Missouri River from Gavins Point Dam to Maskell.

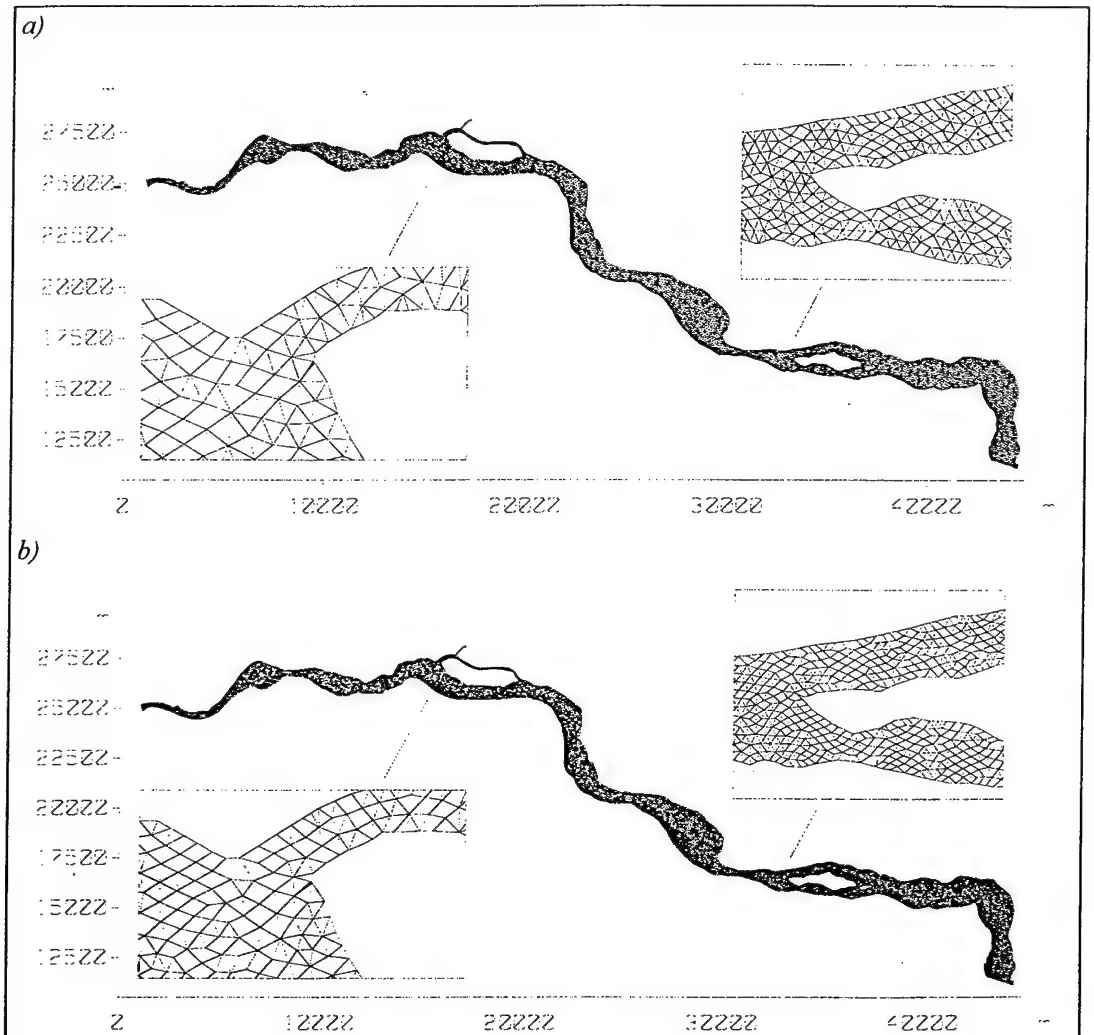


Figure ~~3-2~~ 4.3 Finite element meshes of the Missouri River from Gavins Point Dam to Maskell, (a) low resolution Mesh 1 and (b) high resolution Mesh 2.

4.3 Bathymetric Data

The bathymetric data in a 2D hydraulic model is one of the most important factors in attaining high quality simulations. The quantity and quality of the bathymetric data is therefore of utmost significance.

Along this reach of the Missouri River the bathymetry was obtained by the MRD in 1995 by echo sounder surveys of channel cross sections. In total 343 cross sections were available along the 55 km reach creating an average spacing of just over 150m. Each cross section was made up of between 30 and 200 data points, depending on section length. The typical spacing between data points along a section was 6m. All elevation data was converted to metres. Bathymetric data was missing on the cross sections where the bed was above the water surface, such as on sand banks and mud flats. In these regions the topographic elevation was estimated from United States Department of the Interior 7.5 minute quadrangle maps, except on the permanent island in the model where no such data is required.

The bathymetric data must now be applied to the finite element mesh. This is the process of interpolating between topographic data points and assigning elevation (z) values to the nodal points in the mesh. This produces a geometry file for the model simulation. The interpolation is usually carried out using STBTEL, the TELEMAC sub-program. This uses a quad-directional interpolation routine, taking the nearest data point in the four quadrants around each node, weighting for distance from the node and combining to give the nodal elevation. An alternative interpolation routine has been written at Bristol for use with cross sectional data of river channels. This is a linear interpolation down the line of greatest depth between sections and improves the definition of this line in such cases as the Missouri River. A portion of the models topography is shown in Figure 4-4.

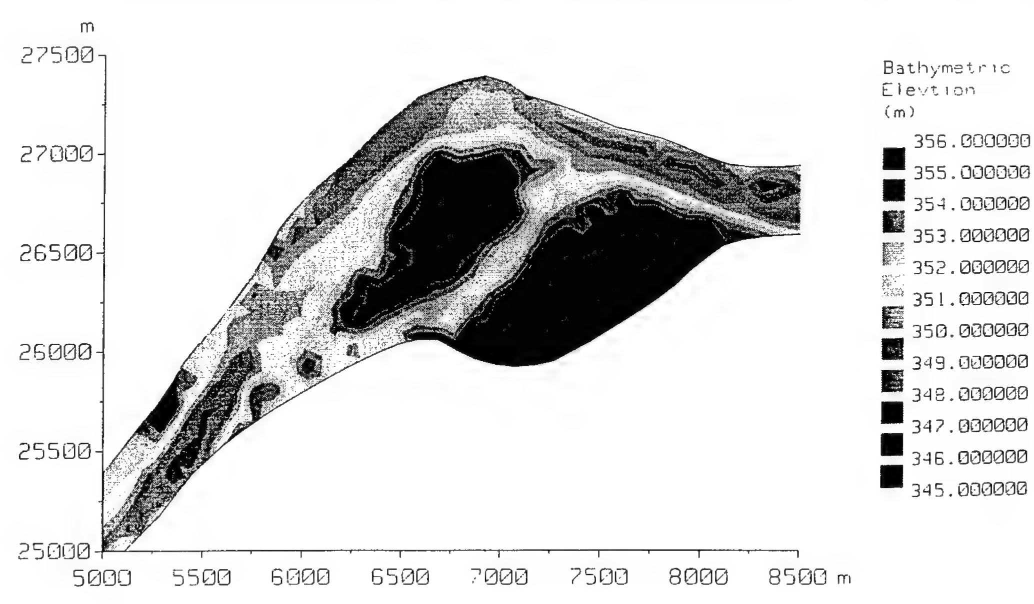


Figure 4-4 An example portion of the models bathymetric representation. This section is immeadiately upstream of Yankton.

4.4 Boundary Condition Specification

The boundary conditions of the model are very important to the simulations run. There are several boundaries to each model that must be set with care prior to the model run. These boundaries are divided into two types, liquid boundaries and solid boundaries.

With the Missouri model the liquid boundaries, allowing flow across them, are at the top and bottom ends of the reach and on the James River tributary inflow. Model inflows are prescribed as flowrates, at Gavins Point Dam and from the James River, and outflows as water surface elevations, at Maskell. This produces a well posed problem for fluvial flows according to the theory of characteristics (Hervouet and Van Haren, 1995). All measured flowrates were converted to m^3/s (cumecs) and stage values to metres.

Solid boundaries allow no flux across them. They are found down the sides of the reach and through the bed. The side boundaries in the Missouri model are set as slip boundaries, allowing a velocity along them. This is justified by the size of the elements making flow overly restrained in areas of channel constriction when the more realistic no-slip boundaries are imposed. The flexible boundary of the flow field removes this problem for large portions of the reach where such an argument is irrelevant.

4.5 Physical Parameter Specification

The two most important physical parameters in fluvial hydraulic models are generally agreed to be bed friction and turbulence (Baird and Anderson, 1990; Bates *et al.*, 1992). The theory of the two in TELEMAC-2D has been discussed in section 3.4. They are the only two considered in any detail here.

Given the channel only nature of the model and lack of additional information the bed friction and turbulence parameters were defined as constant throughout the entire reach. These are obviously simplifications but should be adequate as a first approximation. The bed friction is always defined using Manning's law enabling the standard Manning's 'n' measure of flow resistance to be used. The turbulence was defined using the zero-equation velocity diffusivity representation.

5. COMPARISON OF MODEL PREDICTIONS TO OBSERVED DATA

5.1 Methods of Comparison

The data available for this study is stage data at two sites within the model domain which can be considered internal but 1-D and numerical. The satellite images are also internal but 2-D and numerical (except for example of process validation that shall be shown later). The satellite imagery is therefore the more powerful validation data type. How well the observed and predicted match shall be shown in the following sections and at the end this idea of strength of validation shall be revisited in the light of the results. Firstly however the methods of model application used in this study and elsewhere are reviewed.

Usually when hydrological models are applied to actual scenarios a two stage process of model calibration and validation is carried out. Calibration is the process by which parameter values are varied within reasonable ranges until the differences between observed and computed values are minimised (Konikow and Bredehoeft, 1992). Theoretically speaking, physically based model should not need calibrating. The estimation and application of physically realistic parameter values for the model should enable the model to perform well without any further manipulation. However the numerous simplifications involved in modelling and problems in parameter estimation mean that such a notion is unrealistic. Calibration is therefore performed on virtually all physically based hydrologic models. Following the calibration phase the model must then be validated. In most cases the calibrated parameter values are used again on a different portion of the flow record to see if they enable a good match between observed and predicted variables. If they do then the model and parameters are considered validated and can be used with confidence for prediction of future events. If not then calibration and possibly some stage of model formulation must be repeated until the model is validated. It should be noted at this point that validation is used here to mean that a reasonable comparison is obtained between observed and predicted data rather than that the model has been shown to be a accurate representation of the system.

With this application of TELEMAC-2D the highly structured methodology for calibration and validation outlined above is not entirely appropriate for several reasons:

- this study is for research of model behaviour,
- the number and variety of data sources make its application difficult,
- there is no need to produce a model capable of predicting future events at this stage,

The two processes are therefore not used as distinct entities in the following investigation. Instead a hybrid of the two forms was used enabling all benefits of the calibration-validation procedure to be accrued but also much more. The model was therefore run using a wide range of bed friction values over several sections of the flow record. This enabled the calibrated parameter values to be found for each comparison data set (2 internal stage gauges and possibly some areas on a satellite image). Cross comparison of parameter values and the assessment of errors when the model was calibrated onto one data source allowed an assessment of the model/parameter performance more complete and powerful than with the traditional calibration-validation procedure.

The time period being simulated for this comparison is around 6th June 1994 synchronous to the LANDSAT-TM satellite image of the area that will be used in section 5.3. The flow record around this date showed very little (<2%) variation in the data set. The simulation was therefore taken as a simple steady state computation, simplifying the analysis of results. All

the following comparisons are therefore done on a single point in time basis, e.g. a single water level for each point in the domain for each parameter set.

5.2 Comparison of model prediction with internal stage data

Two internal gauges for water level are available for the reach of the Missouri River described in section 1. The gauges are at Yankton, 7.5 km down the reach, and Gayville, 21.5 km down the reach (Figure 4-1). Hourly stage records are available for these gauges.

The sensitivity of the model prediction of the water depth at these two locations has been shown to be dependant predominantly on the bed friction parameter. This is the only parameter varied in the following analysis. Other parameters would have only minimal effect but increase complexity greatly. The sensitivity of water depth to friction is virtually linear at both internal gauge sites (Figure 5-1) and in the expected direction, i.e. water depth increasing as friction increases.

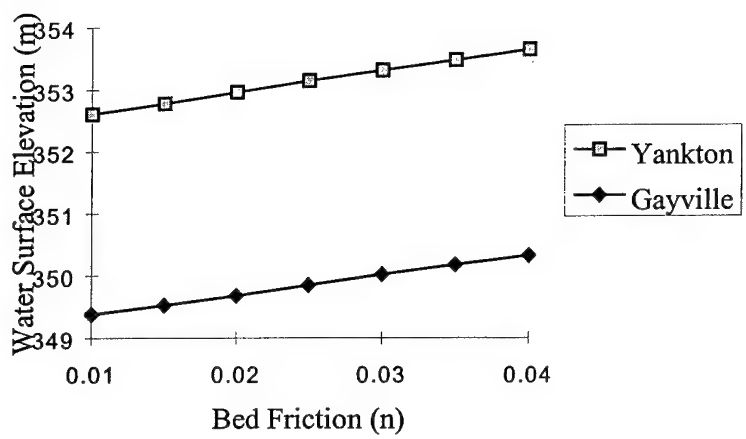


Figure 5-1 Linear sensitivity of water surface elevation to bed friction at the two gauge sites, Yankton and Gayville.

This finding allows the use of McCuen's (1973) linearized sensitivity equation but a simple regression equation is more useful for applying the results in this analysis and is therefore used here. Equations were produced for the model behaviour at both sites, Yankton and Gayville, relating the error in water level prediction to the bed friction (Manning's 'n') parameter. The equations, calculated using the statistical computing package MINITAB, can be written thus:

Yankton Error = -0.410 + 34.72 n
Gayville Error = -0.976 + 31.93 n

Alternatively they can relate the water depth to the bed friction thus:

Yankton Water Depth = 4.87 + 34.72 n
Gayville Water Depth = 2.91 + 31.93 n

The confidence in these regression lines is huge with tiny residuals (<0.015m) in all cases. These equations can therefore be used as a very powerful tool for estimating model

predictions for 'n' values at which the model has not been run, although it should not be extrapolated beyond the range of 'n' values used to make the relationship (i.e. 0.01 to 0.04). At present this is only shown at two points but could perhaps be applied at every node.

It can easily be calculated from the above equations that the 'n' value to eliminate the error in water surface elevation at Yankton is 0.0118 whereas at Gayville it is 0.0306. The power of the above regression equations can now be utilised to calculate the error in the other observation whilst one is correct. Whilst the stage at Yankton is predicted correctly at Gayville the prediction is 0.60m too low. Reversing this, whilst Gayville is predicted correctly the prediction at Yankton is 0.65m too high. In percentage terms these errors are 18.26% and 10.96% of the expected water depth at the two points respectively.

Taking the value central to the above two estimates of Manning's 'n' should enable the approximate calculation of the joint minimum errors in the predictions. This value of 'n' is 0.0212 and produces an error at Yankton of 0.33m and at Gayville of -0.30m. Slight adjustment of 'n' could equalise these errors but would be irrelevant. These errors can be expressed again as percentages of the water depth such that the error at Yankton is 5.89% and at Gayville is 8.37%. Figure 5.2 shows a downstream section of the comparison between observed and predicted water surface values.

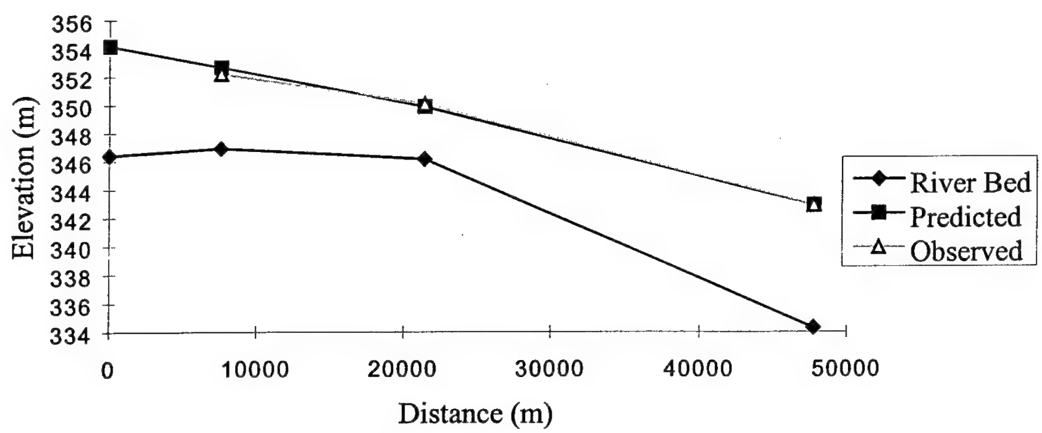


Figure 5-2 Downstream section of the reach showing the elevations of the river bed, observed water surface and predicted water surface (using a bed friction of n = 0.025) at the 4 gauges.

Interestingly the value of rate of change of the water surface (error term or water depth) is different at the two gauging stations. Thus a fixed change in the bed friction produces a different change in the water surface elevation at the two stations. Investigation into how this type of behaviour occurs over the whole reach would be useful in determining more about model behaviour or what causes this phenomenon.

The comparison between observed an predicted stage values has shown that the model is capable of predicting this variable to about 0.3m at two sites simultaneously. This is a good result given the simplicity of the model set up. Given further work on the parameterization this could no doubt be reduced significantly.

5.3 Comparison of model inundation predictions with satellite imagery

Many types of satellite imagery have been used widely in studies of fluvial and coastal hydraulics. The wide coverage, ease of use and wealth of information contained in the images makes them ideal for many uses in this field. Redfern and Williams (1996) review the available sensors and their applications in (primarily coastal) hydraulics. Previously a lot of work has been carried out on the remote sensing of flood extent because of the immense hazard and mitigation costs on floodplain developments. Rango and Salomonson (1974) show that the areal extent of flooding can be mapped using near-infrared sensors on ERTS 1 (Earth Resources Technology Satellite - later renamed Landsat). More recently Imhoff *et al.* (1987) use SAR (Synthetic Aperture Radar) and Landsat MSS (Multispectral Scanner) for mapping flood extent and damage in Bangladesh. SAR has been shown to very accurate for flood boundary delineation by Biggin and Blythe (1996) on the River Thames in the UK. Satellite remote sensing of the 1993 floods on the Mississippi and Missouri Rivers in the USA with both SAR (Brackenridge *et al.*, 1994) and Landsat TM (Thematic Mapper) have further shown the potential of such methodology.

Satellite data has also been used to measure flood stages as illustrated by Koblinsky *et al.* (1993) using the U.S. Navy's Geosat radar altimeter on the Amazon basin and Brackenridge *et al.* (1994) using SAR data and topographic maps on the Mississippi. Both methods have quite large errors associated with them at present.

Plumes of sediment rich water can also be identified as they have a higher reflectance than clear water in the visible region of the spectrum (Lillesand and Kiefer 1987). Brackenridge *et al.* (1994) use this factor to highlight levee breaches along the Mississippi River during the 1993 floods, the breaches acting as a sediment sources, and explain sediment deposition patterns. Other forms of pollution and thermal emissions can also be traced (Lillesand and Kiefer, 1987).

The availability of satellite imagery for the modelled reach of the Missouri River synchronous to the flow records has enabled several fundamental research objectives to be addressed. Data from satellite images is ideal for use with 2-D fluvial hydraulic models being of a scale commensurate to the model resolution and being widely spatially distributed. In this study such data has the potential to be used for:

- validation of inundation extent predictions,
- identify regions of error,
- calibration data,
- process validation.

Remotely sensed data has the potential to be used more widely in hydraulic modelling for topographic and physical parameterization (Bates *et al.*, 1997) but these are ongoing research themes.

Two sites at which to analyse model inundation predictions were chosen. These were selected specifically because of their complex bathymetry and topography, involving mud flats, permanent and temporary islands. The location of the two sites are shown on Figure 5-3. Side by side comparisons of the observed and predicted inundation are to be made using different friction values at both sites followed by an overlay showing the geo-referencing that can be done to the results.

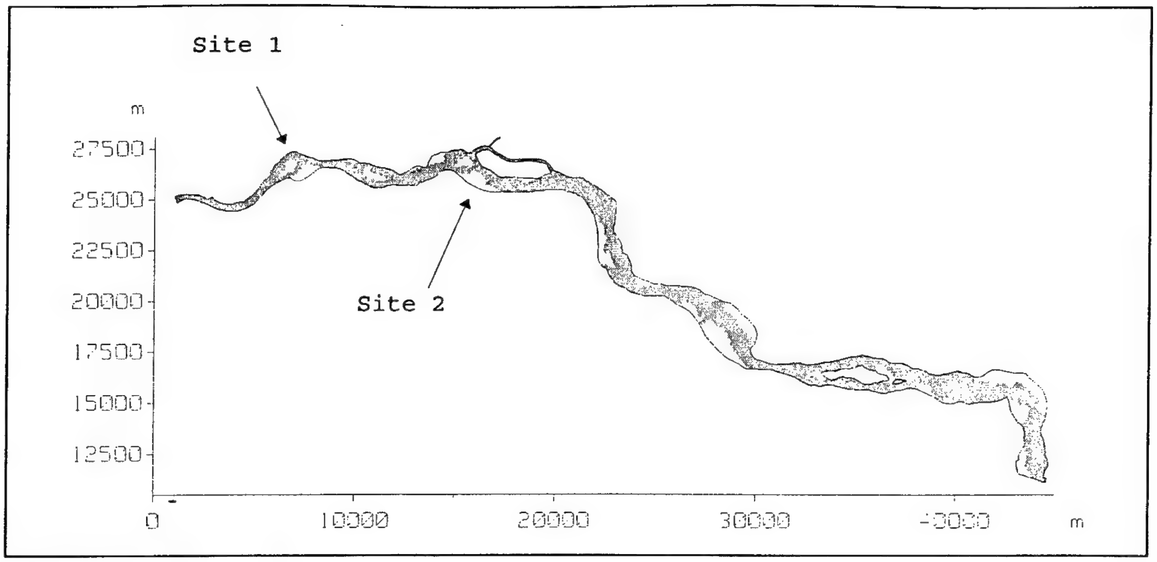


Figure 5-3: Locations of the two sites to be used in the comparison of model predictions with satellite imagery.

The side by side comparisons of the model predictions against the Landsat TM image, using bed friction values of 0.01, 0.02, 0.03 and 0.04, are shown in Figure 5-4 and Figure 5-5 for the two sites. These figures plot the satellite image against the predicted flow field boundary as this is the model result that can be directly compared to the image. From these it can be seen that the model predictions are generally good, producing a close spatial match against the observed data. This allows calibration of the model to be carried out with such data by varying bed friction until there is a close spatial match between observed and predicted. This variable behaviour is caused by the gradient of the topography around the water surface. If the topography has a shallow gradient then changes in the bed friction, changing the water depth, causes changes in the inundated areas. Where the topographic gradient is steeper then the same changes in water depth shall have virtually no impact on inundated area. A problem arises in this specific case, as far as calibrating the model on this data, because the topography above the water surface was only estimated from US Department of the Interior maps and is therefore probably not of the accuracy required to enable much confidence to be placed in the predictions of inundated area on islands.

Figure 5-4: Comparison of Landsat TM image and 4 alternative model predictions with different bed friction (Manning's 'n') values at site 1.

Figure 5-5: Comparison of Landsat TM image and 4 alternative model predictions with different bed friction (Manning's 'n') values at site 2.

By geo-referencing the model results and satellite image an overlay of the two can be made. An example of such is shown in Figure 5-6 for a section of this reach. This detailed comparison between observed and predicted flow field boundary enables problem areas to be pinpointed and further model development to proceed by further data collection or adjustments to the model in these areas.

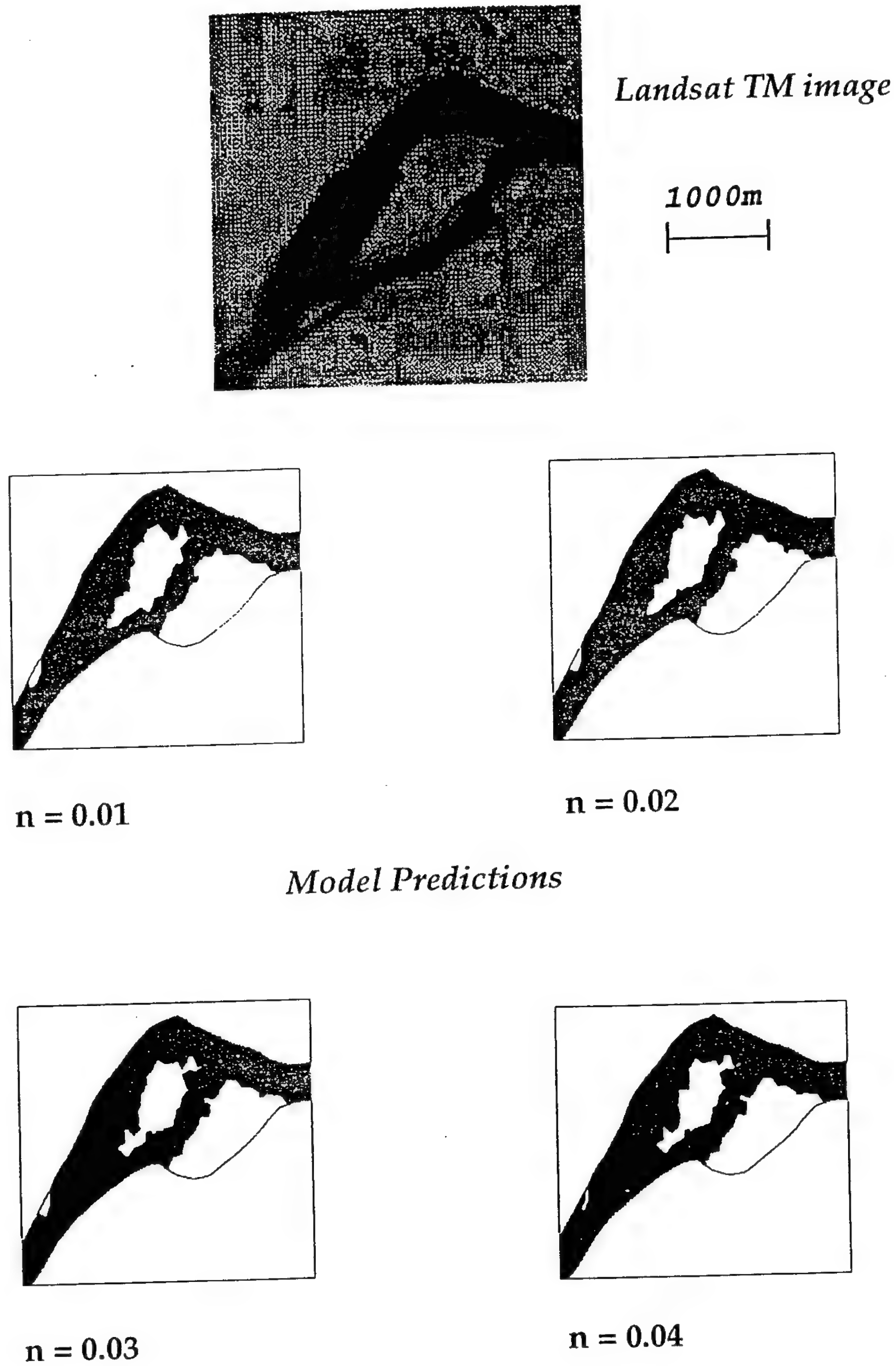
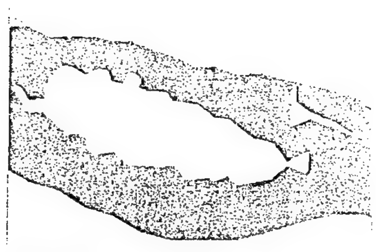


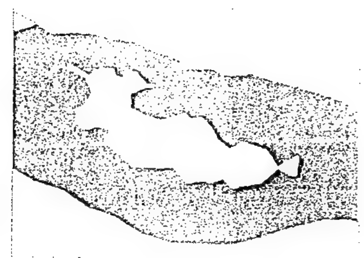
Figure 5-4a Comparison of Landsat TM image and 4 alternative model predictions with different bed friction (Manning's 'n') values at site 1 for event 1.

Landsat TM image

1000m

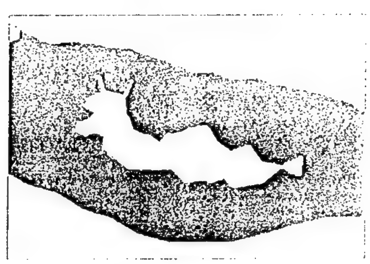


n = 0.01

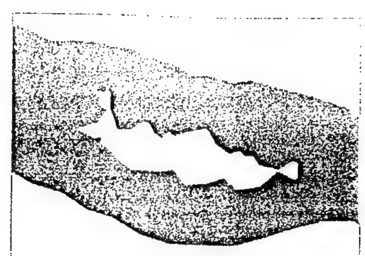


n = 0.02

Model Predictions



n = 0.03



n = 0.04

Figure 5-4b Comparison of Landsat TM image and 4 alternative model predictions with different bed friction (Manning's 'n') values at site 2 for event 1.

Figure 5-6 An overlay of the model prediction of flow field boundary onto the Landsat TM image for a region around Goat Island (including sites 5 and 6) for event 1.

5.4 Summary

These first simulated flow conditions have shown the both the excellent predictions of the 2-D hydraulic model and the utility of the data sources to validate its performance. The internal stage data was matched at single points but not so closely at both points simultaneously. The inundation extent was validated against the satellite images very well. Some areas showed up problems in the models bathymetry/topography. Given possible future refinements in the model set-up the internal stage data should be able to be matched simultaneously at both sites quite easily. Matching all the flow field boundaries shall be more difficult given their dependence on the model bathymetry. This is however expected given the relative strength of the two validation types as discussed earlier.

6. DERIVING BATHYMETRIC DATA REQUIREMENTS

6.1 Initial considerations

The high cost of collecting bathymetric and topographic data must be justified by attaining high quality model results that could not be accomplished with a more basic representation. The impact of the density of cross section on the models bathymetry and model predictions are investigated in this section.

Four realisations of the model bathymetry were created using:

- all the available cross sections (150 m spacing),
- alternate cross sections (300 m spacing),
- one in four cross sections (600 m spacing),
- one in eight cross sections (1200 m spacing).

From each of these data sets the model bathymetry was created at the node points on the low resolution mesh using the directional interpolator described in section 4.3. The model was then run once with each of these representations for the conditions of event 1 with a bed friction value of 0.025.

The impact of these changes on the model bathymetry was profound. Figure 6-1 shows the impacts in one example area (site 6). As can be clearly seen the detail of the bathymetric representation in the model degrades rapidly as the number of cross sections decrease.

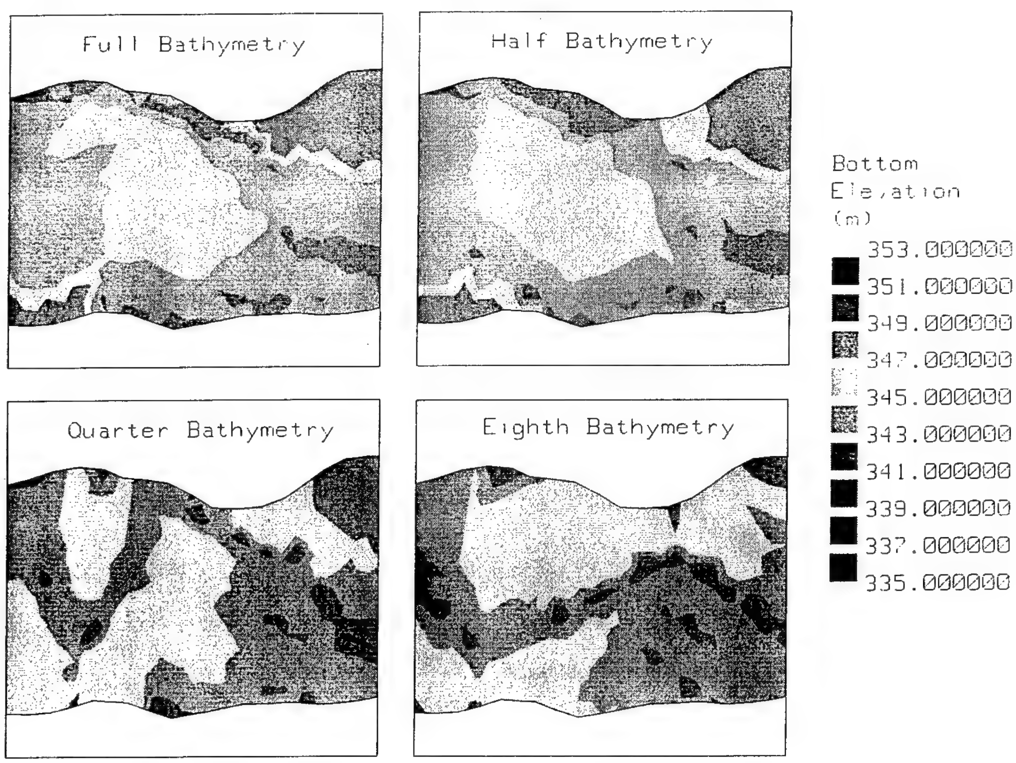


Figure 6-1 Impact of degrading the number of cross sections used on the model bathymetry. The spacing degrades from 150 m to 1200 m across the range illustrated.

6.2 Comparison to observed data

The influence of changing the level of bathymetric data on the water surface elevation predictions at Yankton and Gayville is shown in Table 6-1. From this table it can be seen that at Yankton the level of data provision has minimal effects of the predictions, varying them by only 0.1m compared to an actual error of approaching 0.5m. At Gayville, however, decreasing the bathymetric produces a continuous increase in water surface elevation. The magnitude of the change over the runs is 0.72m, spanning the observed value. The half data set run produces a prediction of water surface elevation at Gayville within 0.015m of the observed value.

Table 6-1 Water surface elevations at Yankton and Gayville for simulations with the various levels of bathymetric data supplied to the model.

Location	Full	Half	Quarter	Eighth	Observed
Yankton	352.667	352.751	352.665	352.721	352.196
Gayville	349.854	349.990	350.398	350.578	350.032

From these results there appears to be little benefit in using the highest density data set as the results are equally good using half the data. The quarter and eighth runs do however show decay in the quality of the results at Gayville. The more important results are however the spatially distributed ones that are now investigated.

Once more the side by side comparisons have been made for model predictions, this time with the 4 levels of bathymetric data, against the Landsat TM image at the two sites of interest (Figure 6-2 and Figure 6-3). In each case the full bathymetry appears to give a favourable comparison against the observed data. Reducing the bathymetric data has a major influence on the spatial predictions. In some cases this manifests itself even when half the data is used such as at sites 1,3 and 6, where the spatial match degrades rapidly. As the data reduction continues huge errors may be introduced.

6.3 Summary

The results from this section have shown the bathymetric data to have a profound influence on the spatial predictions of the 2-D hydraulic model and a lesser influence on the water surface elevation. This fits well with the rigour of validation discussed in section 5. There it was proposed that matching internal stage values was a weaker form of validation than matching 2-D inundation. These results show that a more poorly specified model, i.e. that with less bathymetric data, can match the internal stage values but not the inundation extent. Hence inundation extent validation is a more rigorous test of model performance.

From these results it would seem, as expected, that the highest density of bathymetric data produces the best results. More detailed simulations looking at the relationship between mesh resolution, bathymetric data density and distribution, and interpolation method must be carried out before more detailed guidelines on the optimum level of bathymetric data can be considered.

Figure 6-2: Comparison of the Landsat TM image to model predictions with the 4 levels of model bathymetry at site 1. The bathymetries were created by varying the spacing of cross sections used from 150 m to 1200 m.

Figure 6-3: Comparison of the Landsat TM image to model predictions with the 4 levels of model bathymetry used at site 2. The bathymetries were created by varying the spacing of cross sections used from 150 m to 1200 m.

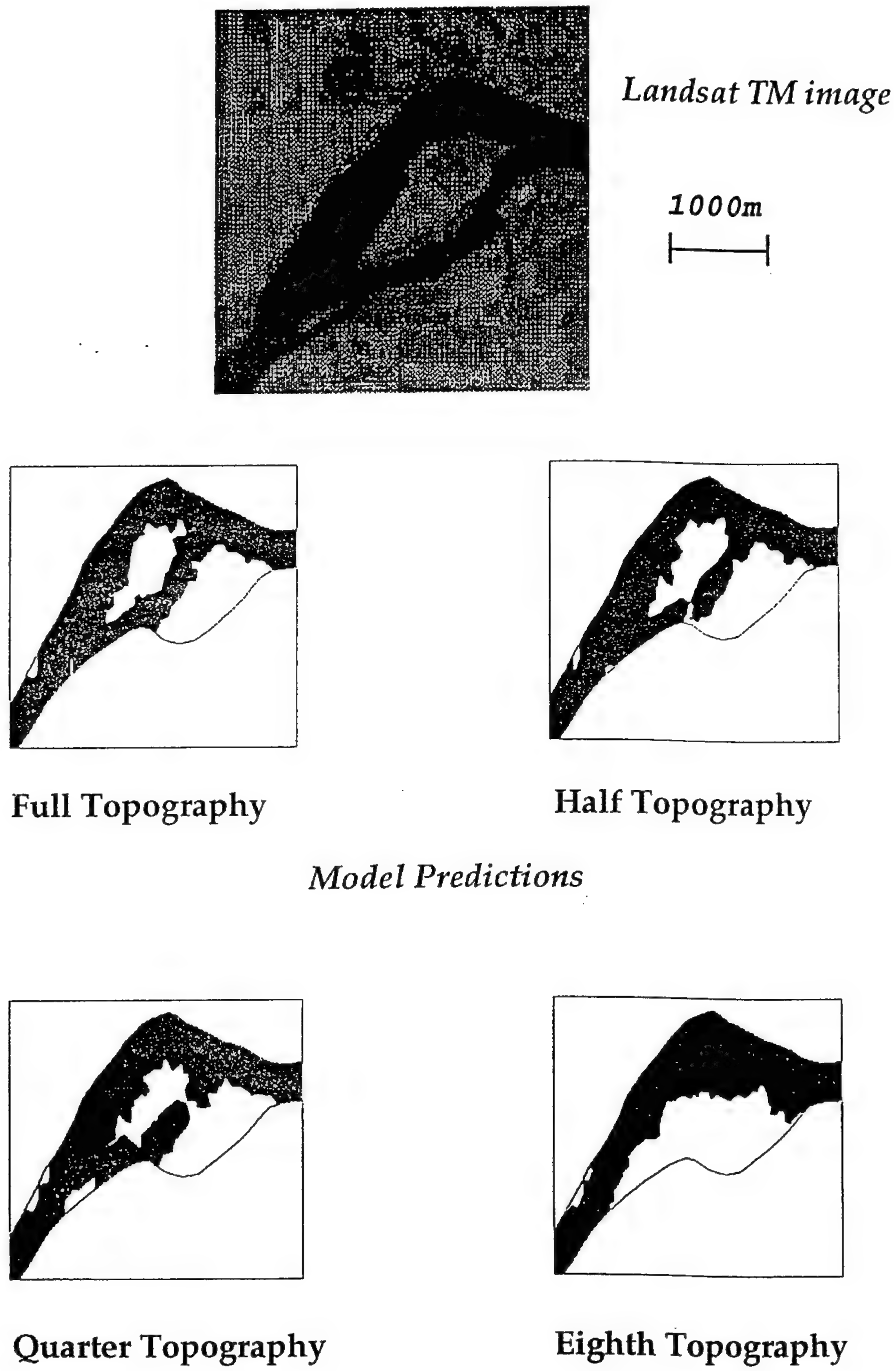


Figure ~~7-2a~~ 6.2 Comparison of the Landsat TM image to model predictions with the 4 levels of model bathymetry used for event 1 at site 1. The bathymetries were created by varying the spacing of cross sections used from 150 m to 1200 m.

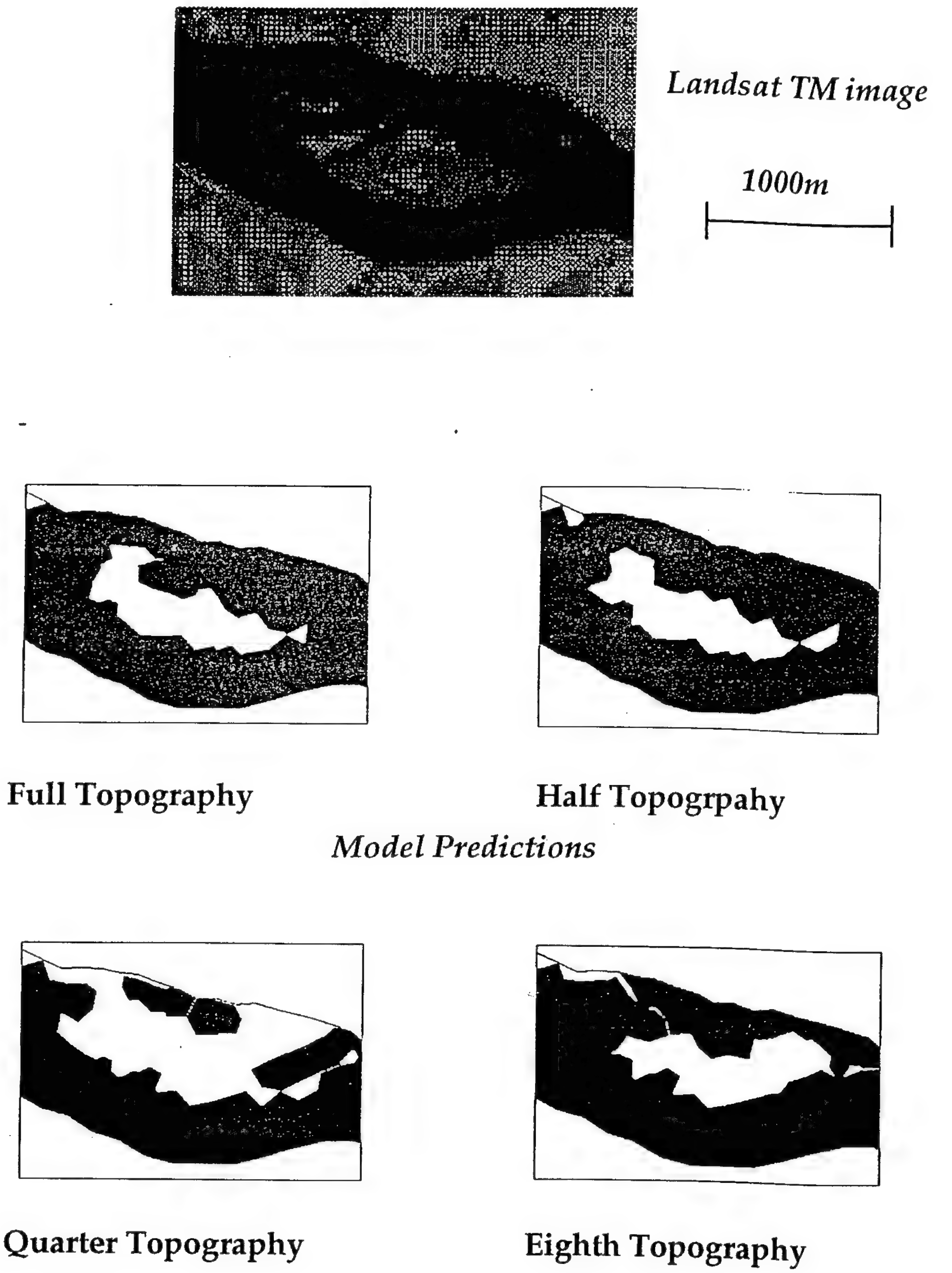


Figure ~~7.2~~ 6.3b Comparison of the Landsat TM image to model predictions with the 4 levels of model bathymetry used for event 1 at site 2. The bathymetries were created by varying the spacing of cross sections used from 150 m to 1200 m.

7. CONCLUSIONS

This modelling study of a 55 km reach of the Missouri River has illustrated the capability of high resolution, physically based fluvial hydraulic models for accurate flow representation. A hydraulic model was created for the reach of interest, between Gavins Point Dam and Maskell, using the TELEMAC-2D modelling system. A sensitivity analysis of the model showed bed friction to be the dominant parameter governing model performance. Extensive validation of the model predictions was carried out against both internal stage data and satellite imagery of flow field boundaries. Finally the impact of mesh resolution and bathymetric data provision was briefly examined.

The key findings of this study can be summarised thus:

- A state of the art two-dimensional hydraulic model can simulate fluvial hydraulics accurately on this scale in both steady state and dynamic conditions.
- Model predictions can be matched to stage data internal to the model domain with a high degree of accuracy for initial simulations (Figure 5-2). Improvements to the match could no doubt follow with further model developments.
- Spatial distribution of flow field boundaries has been shown to be accurate in most cases by comparison to satellite imagery (Landsat TM) (Figure 5-4 and Figure 5-5).
- Partial model validation has been graded by its rigour. Matching 2-D inundation data is considered more powerful than matching internal stage data, a hypothesis corroborated by model predictions with varying specifications of bathymetry (Figure 6-2, Figure 6-3 and Table 6-1).
- A degree of process validation was achieved against satellite imagery in a specific case (Figure 5-6).
- The relationship between mesh resolution and bathymetric data is vital to model specification but requires further study to quantify.

8. RECCOMENDATIONS

There remain however, many areas where further work could improve the model predictions.

- The fundamental complexity and connection of mesh and bathymetry is a limiting factor whilst a) only limited bathymetric data is available and b) computational expense must be considered when making meshes. Until meshes can be much more finely resolved and the bathymetric data available to apply to them at a commensurate scale then this problem of bathymetric representation and its impact on model predictions shall remain. Further data collection in specific problem areas could mitigate the problem in this specific case.
- The model set-up used here in terms of parameters was extremely simple and as such model results were not as good as they could be following further modifications. With modification of the bed friction parameter, distributing it over time and/or space the errors particularly in internal stage could be reduced dramatically. The 2-D flow field boundaries are however more dependant on the bathymetry than the parameter distribution.
- With the knowledge gained from the simulations carried out already the model structure could be modified to include more permanent islands where they are evident and vary the mesh resolution over the domain where the gradient of predicted variables are greatest.
- Now that model validation has been somewhat structured the possibility exists for deliberate data collection in order to validate specific outputs of the model to produce as strong and complete a validation as possible. For example more 2-D process data could be collected in order to validate the most fundamental aspect of a 2-D hydraulic model.

The ever progressing capability of highly resolved 2-D fluvial hydraulic models, including flows over dry areas, opens up a wide range of potential applications that include:

- Predicting the impact of anthropogenic activity
- Flood hazard assessment
- Geomorphological and hydrological process studies
- River management schemes

This report has shown that the capability now exists for high resolution fluvial hydraulic modelling to be applied over long (>50 km) reaches with a high degree of accuracy. The use of wetting and drying algorithms allows the simulation of dynamic flows over initially dry areas and their retreat. This capability opens up a wide range of potential applications especially for the "what if" type modelling vital for controlled management and development of river systems.

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Figure Captions

Table Captions